Three active neutrinos

Patrick Huber

Center for Neutrino Physics – Virginia Tech

Workshop on the Intermediate Neutrino Program
Brookhaven National Laboratory, Upton, NY
February 4 – 6, 2015

Status quo

A common framework for neutrino data w/o SBL anomalies is oscillation of three active neutrinos

- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m^2_{31} \sim 2 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \sim 0.16$

This implies a lower bound on the mass of the heaviest neutrino

$$\sqrt{2 \cdot 10^{-3}\,\mathrm{eV}^2} \sim 0.04\,\mathrm{eV}$$

but we currently do not know which neutrino is the heaviest.

Mixing matrices

Quarks

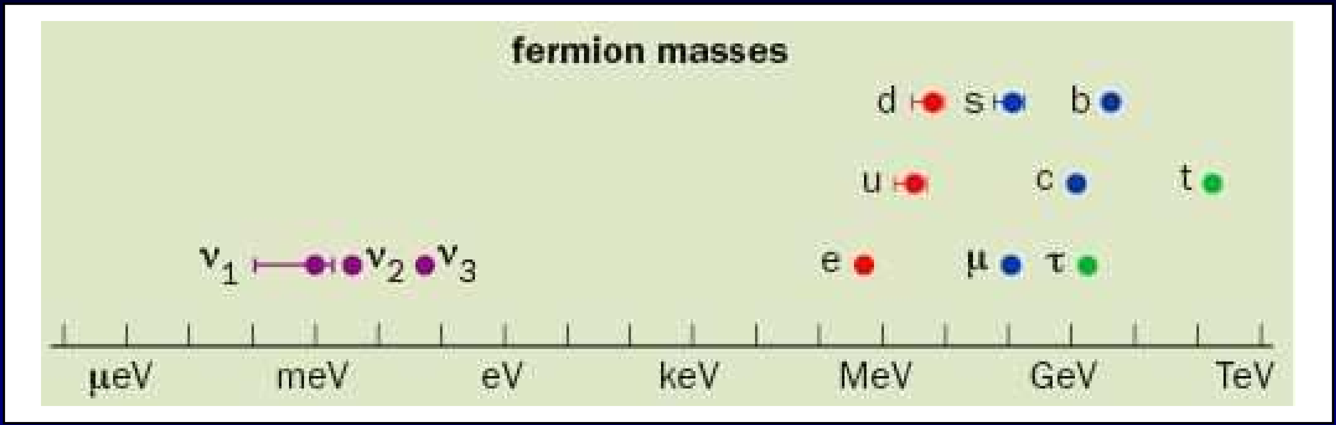
$$|U_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Neutrinos

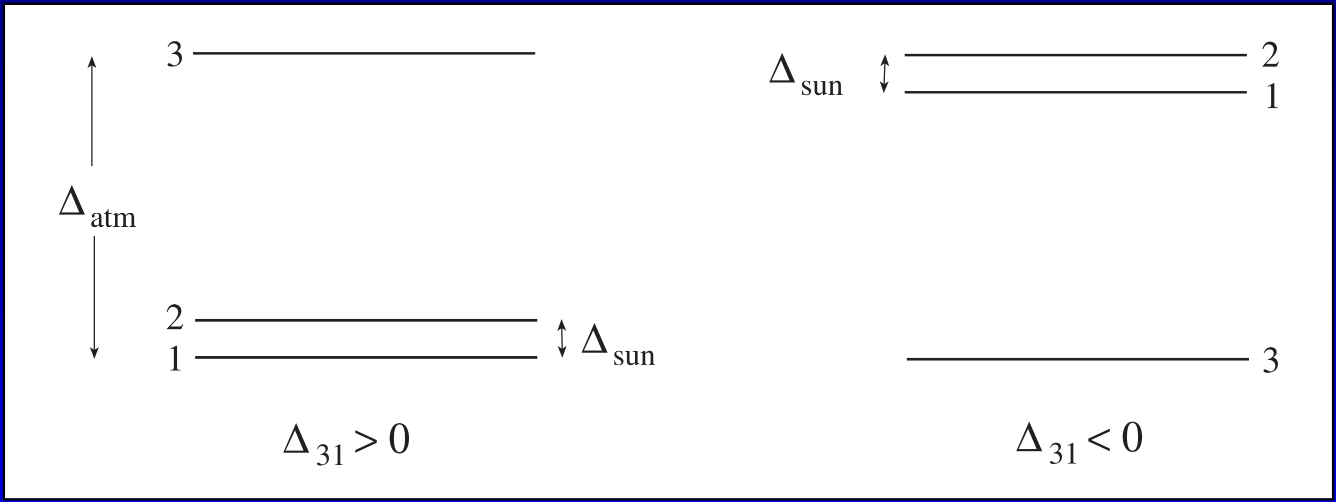
$$|U_\nu| = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Fermion masses

Scale



Ordering – mass hierarchy



Neutrino masses are different

The crucial difference between neutrinos and other fermions is the possibility of a Majorana mass term

$$-\frac{1}{2}m_L(\bar{\psi}_L\psi_R^C + \bar{\psi}_R\psi_L^C) - \frac{1}{2}m_R(\bar{\psi}_R\psi_L^C + \bar{\psi}_L\psi_R^C)$$

on top of the usual Dirac mass term

$$m_D(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

This allows for things like the seesaw mechanism (many versions) and implies that the neutrino flavor sector probes very different physics than the quark sector.

Open questions

In the context of oscillation of three active neutrino flavors, the open experimental questions are

- Is θ_{23} maximal and if not what is the octant?
- What is the mass hierarchy?
- Is there CP violation in the lepton sector?
- Is the three flavor framework complete?

What impact will the answers to these questions have on our theoretical understanding of neutrinos?

CP violation

There are only very few parameters in the νSM which can violate CP

- CKM phase – measured to be $\gamma \simeq 70^\circ$
- θ of the QCD vacuum – measured to be $< 10^{-10}$
- Dirac phase of neutrino mixing
- Possibly: 2 Majorana phases of neutrinos

At the same time we know that the CKM phase is not responsible for the Baryon Asymmetry of the Universe…

For me, personally, the fact that neutrino masses are the first (particle physics) evidence for an incomplete Standard Model seems to point to neutrinos as a likely place for even more BSM physics, maybe sterile neutrinos?

The data supporting the idea that all there is, is CKM-like mixing of three flavors is quite weak, certainly order 10% deviations are still allowed.

The absence of convincing models does not convince me of the absence of exciting physics – *cf.* many convincing models of TeV-scale BSM but no experimental hints for TeV BSM